

THEORETICAL RESULTS ON THE DOUBLE-COLLECTING TANDAM JUNCTION SOLAR CELL

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SUMMARY

Results of computer calculations using a one-dimensional model of the Silicon Tandem Junction Solar Cell (TJC) with both front and back current collection are presented. Using realistically achievable geometrical and material parameters, our model predicts that with base widths of 50 μ m and 100 μ m and base resistivities between 1 ohm-cm and 20 ohm-cm, beginning-of-life (BOL) efficiencies of 14% to 17% and end-of-life (EOL) efficiencies of 12% to 14%, after about seven years in synchronous orbit, can be obtained.

INTRODUCTION

Both theoretical (ref. 1,2) and experimental (ref. 3) results show that the back-only collection Tandem Junction silicon solar cell (TJC) suffers a significant degradation in efficiency after exposure to 1 MeV electron fluences greater than 10^{14} electrons/cm². The reduction of the short-wavelength (<0.6 μ m) spectral response to negligible values at high fluences of 1 MeV electrons indicated that the one primary cause of the radiation-induced degradation was the reduction of the base diffusion length and hence of the minority carrier collection efficiency by the back-only collector contacts.

It was reasoned then that with current collection from both the front and back n^+ regions, as shown in figure 1, the radiation degradation could be significantly reduced while still retaining the advantages offered by coplanar back contacts. In the double-collecting TJC structure of figure 1, the front metal grid fingers may be wrapped around one edge of the cell and connected to the bus bar of the metal fingers contacting the back n^+ stripes. The structure could then be regarded as either a TJC with additional collection from the front or as a conventional wraparound contact solar cell with additional collection from the interdigitated back n^+ stripes. However, since the primary current collection would be expected to be from the front, one would expect the structure to behave more like a conventional front-collecting solar cell with respect to radiation degradation. It would clearly be of interest to see if, in theory, this double-collecting TJC structure offers a higher BOL efficiency and higher radiation tolerance than either the front-only collecting wraparound

contact solar cell or the back-only collecting tandem junction solar cell. To this end, we derived a one-dimensional model of the double-collecting TJC.

THEORETICAL MODEL

The model of the double-collecting TJC was derived by considering this device as a composite of eight solar cells in parallel, corresponding to the front surface being illuminated or dark (under metal grid fingers), the surface recombination velocity at the front surface being low or high (allowing for dotted front metal contacts), and the back surface being n^+ collector or not. The Ebers-Moll type currents were calculated for each of the eight cells under appropriate boundary conditions and added to give the overall illuminated current-voltage characteristic of the device. The model also accounts for separate series resistance components in the emitter, base and collector current paths as shown in figure 2, and allows the calculation of all performance parameters as functions of the geometrical and material parameters, and 1 MeV electron fluence.

Computer calculations were made using this model for various base resistivities, base widths, base diffusion lengths, surface recombination velocities and 1 MeV electron fluences. The results of these calculations are presented in this paper. All calculated results are for a 2 cm x 2 cm double-collecting TJC with 18 grid fingers on the front face, 36 n^+ and p^+ interdigitated stripes in the back and the total back n^+ and p^+ areas of 3.4 cm² and 0.4 cm² respectively. The nominal values of all other parameters used in the calculations are given in table 1.

In the radiation damage calculations, two sets of damage coefficients were used. These were the lowest and the highest ranges (curves) from the plots of 1 MeV electron damage coefficient versus p-type silicon resistivity as given by Srour et. al. (ref 4.) and they fit the following equations:

$$\text{Lowest Curve: } K = 1.034 \times 10^{-10} / (\rho_B)^{0.6254} \quad (1)$$

$$\text{Highest Curve: } K = 3.296 \times 10^{-10} / (\rho_B)^{0.6164} \quad (2)$$

where K is the 1 MeV electron damage coefficient and ρ_B is the resistivity in ohm-cms of the p-type silicon base material. The above damage coefficient dependences on base resistivity are based on experimentally determined values and should be valid for base resistivities between 1 ohm-cm and about 50 - 100 ohm-cm. These allowed the calculation of the minimum and the maximum amounts of radiation degradation that can be expected for the double-collecting TJC solar cell for various combinations of geometrical and material parameters. The calculated results are given in the following section.

CALCULATED RESULTS AND DISCUSSION

Figure 3 shows the effect of base width and base diffusion length on the BOL AMO efficiency for a 1 ohm-cm base resistivity solar cell. As would be expected, for a given base width, longer diffusion lengths yield greater AMO efficiencies and, for a fixed diffusion length, the smaller its value, the shorter the base width at which the peak efficiency occurs. Note that since BOL diffusion lengths greater than 300 μ m are now becoming possible for fully processed 1 ohm-cm base material solar cells, BOL AMO efficiency approaching 17% and higher should be possible for the double-collecting TJC.

Figure 4 shows the effect of varying the surface recombination velocity at the uncontacted front and back surfaces on the performance parameters, namely, the short-circuit current I_{sc} , the open-circuit voltage V_{oc} , the fill factor FF and the conversion efficiency η . The results are for a 1 ohm-cm 100 μ m thick cell with a BOL diffusion length of 300 μ m. It is seen that the conversion efficiency is essentially constant for surface recombination velocities less than about 10³cm/s. Thus, it is essential to maintain the surface recombination velocity at less than 10³cm/s. We do not presently have a physical explanation for the very slight improvement in the fill factor for surface recombination velocities greater than 10⁶cm/s.

Figures 5 and 6 show the conversion efficiency η versus 1 MeV electron fluence for 50 μ m and 100 μ m wide cells respectively, for base resistivities of 1, 6 and 20 ohm-cm. The solid curves in each figure correspond to the lowest range of damage coefficients while the dashed curves correspond to the highest range of damage coefficients. Note that, as expected, the theoretical radiation damage behavior of the double-collecting TJC is indeed similar to that of the conventional front-collecting solar cell and much better than that of the back-only collecting TJC (ref 1,2,3). If we define end-of-life (EOL) as an exposure to a fluence of 3×10^{14} 1 MeV electrons/cm² or the equivalent of roughly seven years in geosynchronous orbit, then it is seen from figures 5 and 6 that while the best EOL efficiency is obtained for a 50 μ m thick 1 ohm-cm cell, the least amount of percentage degradation in efficiency occurs for the 50 μ m thick 20 ohm-cm cell. This fact is shown even more clearly in figure 7 which plots the percentage degradation in efficiency versus the base resistivity for 50 μ m and 100 μ m thick solar cells. It is then seen that even with the highest damage coefficient, a percentage degradation in efficiency of 15% can be achieved in a 50 μ m thick, 10 ohm-cm cell whose BOL efficiency would be about 14.5%. On the other hand, if the processing-induced increase of damage coefficient can be almost eliminated so that the lowest damage coefficient curves in figure 7 apply, then a percentage degradation of 15% can be achieved with a 50 μ m thick, 1 ohm-cm cell with a BOL efficiency of about 16.5%.

Figure 8 plots both the BOL and the EOL efficiencies versus base resistivity for 50 μ m, 100 μ m and 200 μ m thick cells. This figure can serve as a design guide in the choice of base width and base resistivity to obtain specified values of BOL or EOL efficiencies.

CONCLUDING REMARKS

The theoretical radiation tolerance of the double-collecting TJC is significantly superior to that of the back-only collecting TJC. Since we have presently not made theoretical calculations on the radiation damage in conventional front-collecting solar cells with identical geometrical and material parameters, no quantitative comparison can as yet be made to the radiation tolerance of these cells.

Using realistically achievable values of geometrical and material parameters, our model of the double-collecting TJC predicts that in addition if the 1 MeV electron damage coefficient in a finished solar cell can be kept as low as in bulk material of the same resistivity, then a 1 ohm-cm, 50 μ m thick double-collecting TJC will degrade by only 15% from a BOL η of 16.5% to an EOL η of 14.1%.

In theory, the double-collecting TJC offers high BOL efficiency, high radiation tolerance, and the convenience of coplanar back contacts. In practice, the greater complexity of fabrication of the double-collecting TJC compared to conventional 50 μ m thick cells with standard or wraparound contacts may be an important consideration in its acceptance as a space solar cell.

REFERENCES

1. Goradia, C.; Vaughn, J.; and Baraona, C.: Theoretical Results On The Tandem Junction Solar Cell Based On Its Ebers-Moll Transistor Model. Conf. Rec. Fourteenth IEEE Photovoltaic Specialists Conference, San Diego, CA, Jan. 1980, pp. 172-177.
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TABLE I
Parameter Values Used in Calculations

Temperature	= 300K
Spectrum	= AMO
Front Refl. Coeff. $R_F(\lambda)$	= Measured values for AR-coated non-reflective surface
Illuminated Area	= 4 cm ²
Number of n ⁺ and p ⁺ Back Stripes	= 36 each
n ⁺ Back Collector Area	= 3.4 cm ² (85% coverage)
p ⁺ Back Stripe Area	= 0.4 cm ² (10% coverage)
p Gap Area in Back	= 0.2 cm ² (5% coverage)
Front Grid Finger Number & Area	= 18, 0.2 cm ² (5% coverage)
Surface Recombination Velocity at uncontacted front and back surfaces	= 10 ³ cm/s
Surface Recombination Velocity at Metal Contacts	= 10 ⁹ cm/s
n ⁺ Emitter and Collector Dopings	= 2.5 x 10 ¹⁹ cm ⁻³
n ⁺ Emitter and Collector Depths	= 0.3 μm
BOL Diffusion Length in n ⁺ Emitter and Collector	= 2 μm
Base Width	= 100 μm, variable
BOL Base Diffusion Length	= 300 μm, variable
Base Resistivity	= 1 ohm-cm, variable
Base Series Resistance	= 0.022 ohm
Emitter and Collector Series Resistances	= Functions of Base Width and Base Resistivity
n ⁺ Emitter and Collector Damage Coefficients	= 2.0 x 10 ⁻⁸ per electron
Base Damage Coefficient	= Function of Base Resistivity

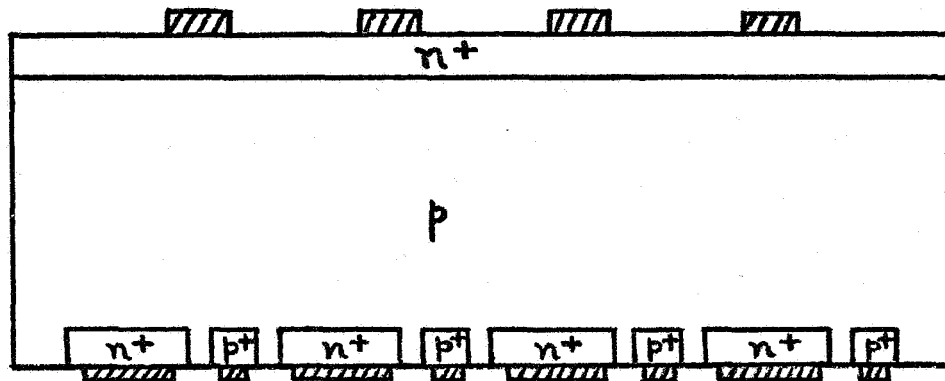


Figure 1. Schematic Diagram of a Double Collecting Tandem Junction Solar Cell.

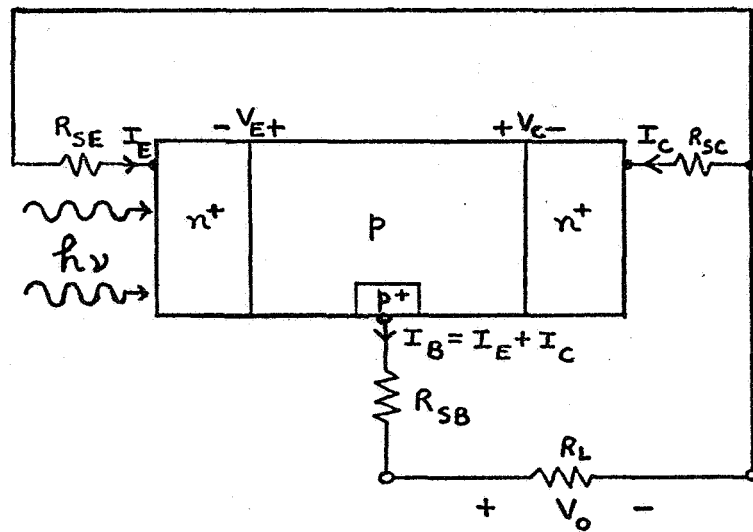


Figure 2. Schematic Representation of Double Collecting TJC With Emitter, Base and Collector Components of Series Resistance.

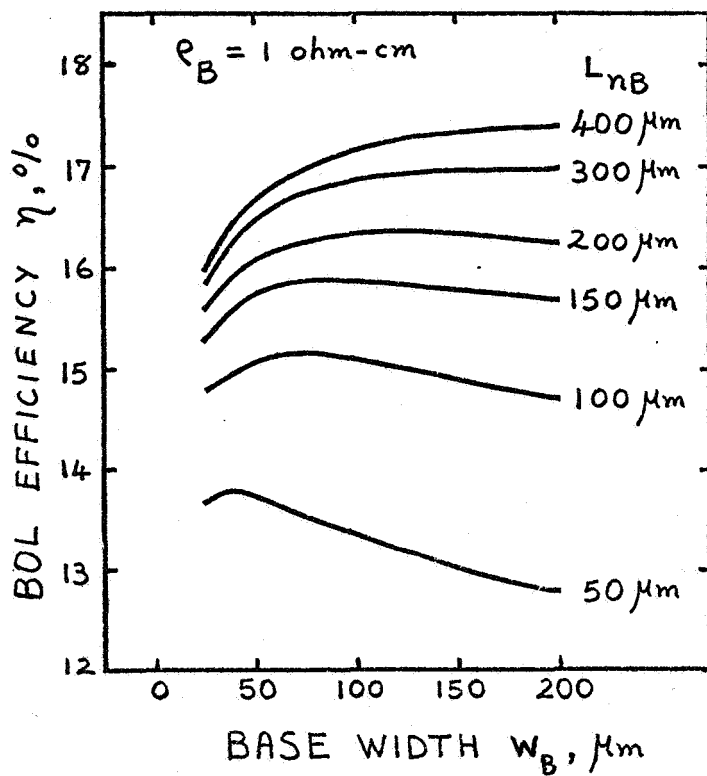


Figure 3. Effect of Base Width and Base Diffusion Length on BOL Efficiency.

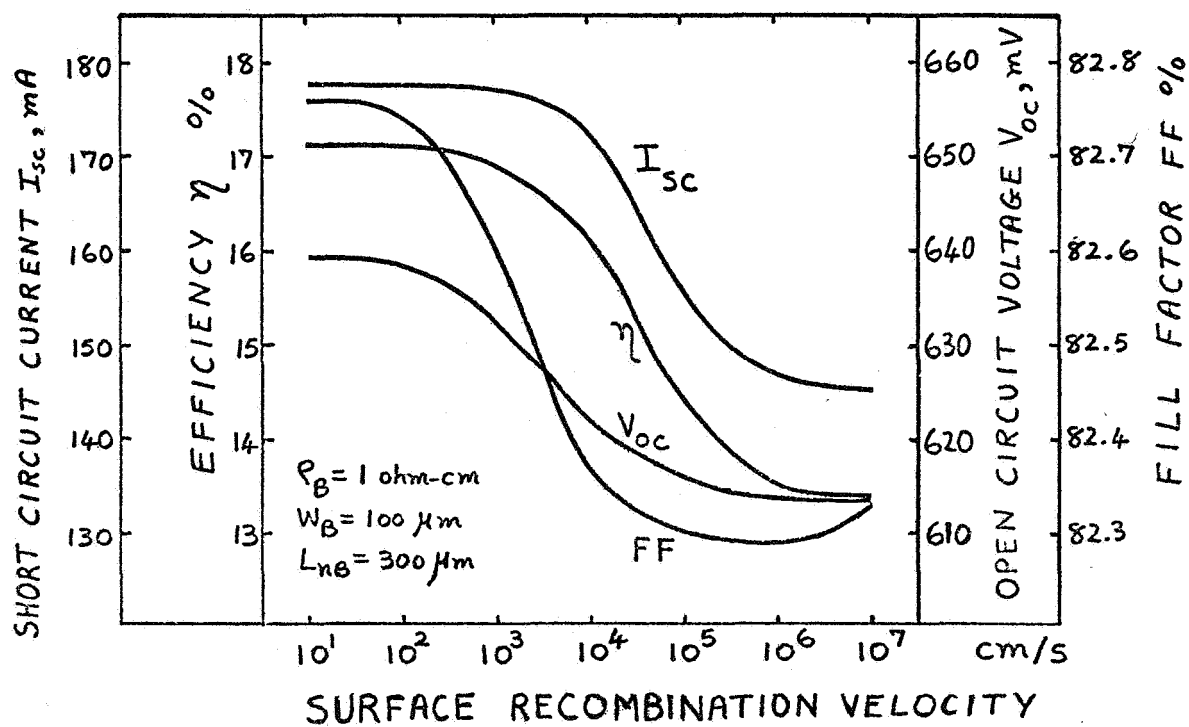


Figure 4. Effect of Surface Recombination Velocity on Performance Parameters.

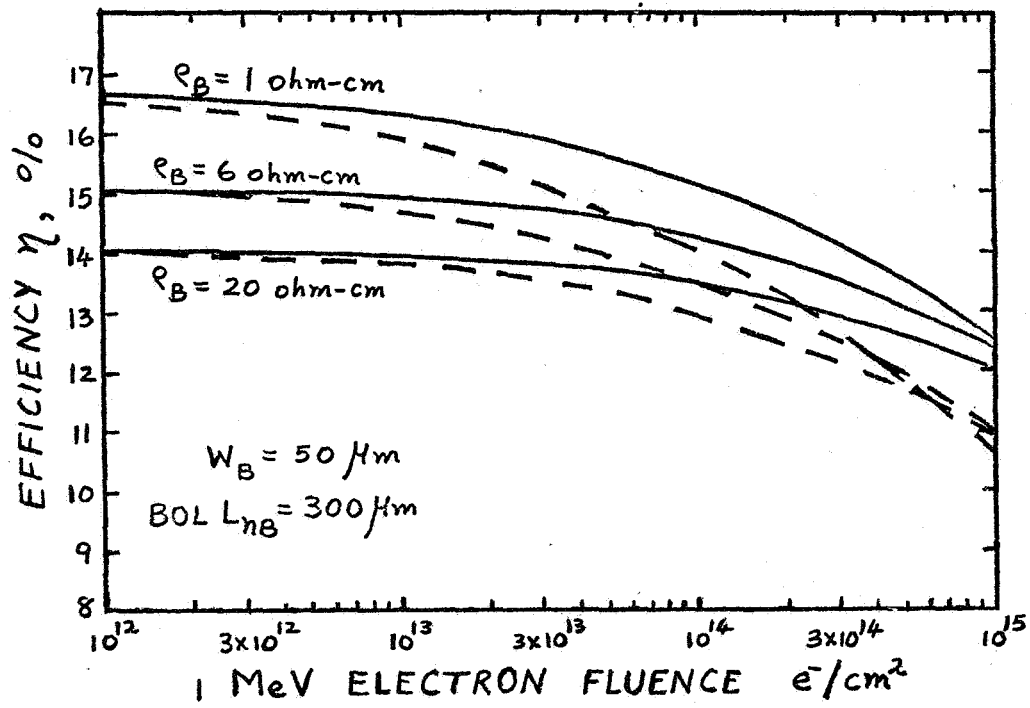


Figure 5. Efficiency versus 1 MeV Electron Fluence for 50 μm Thick Cell.

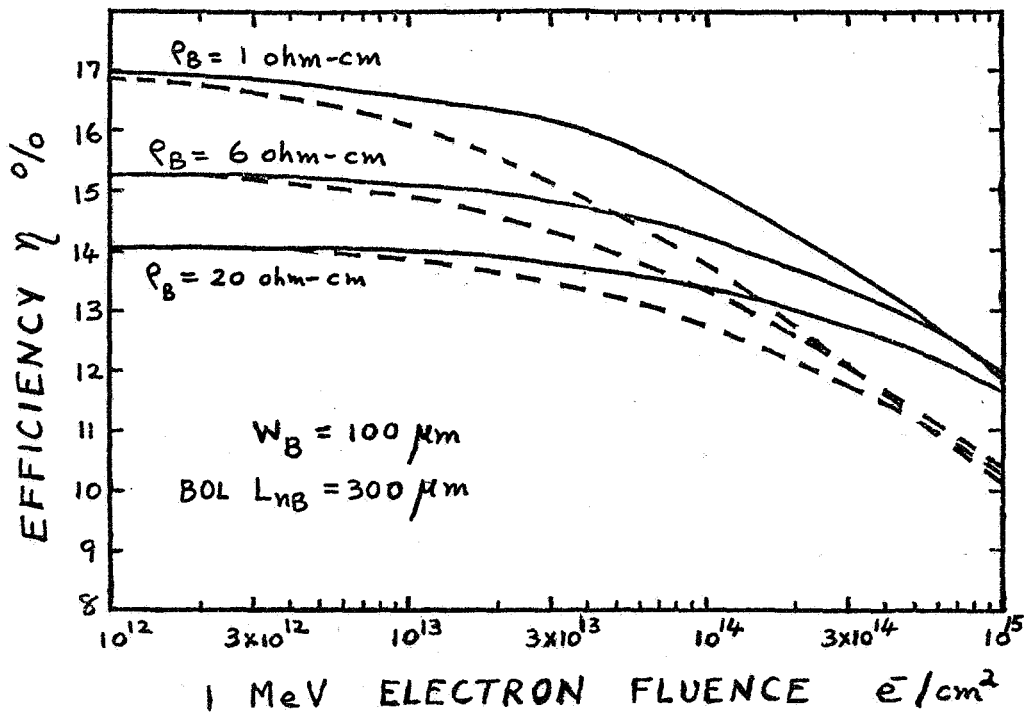


Figure 6. Efficiency versus 1 MeV Electron Fluence for 100 μm Thick Cell.

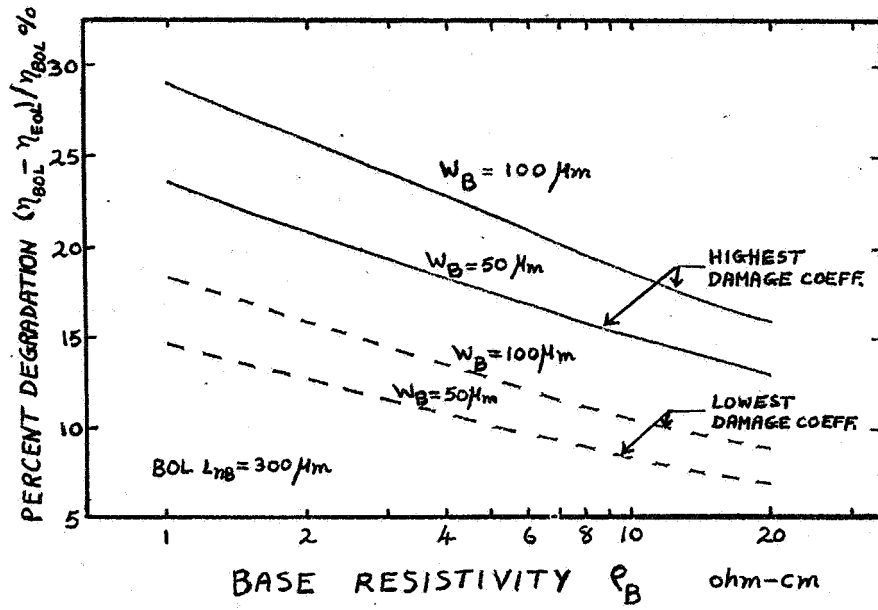


Figure 7. Percent Degradation in Efficiency versus Base Resistivity.

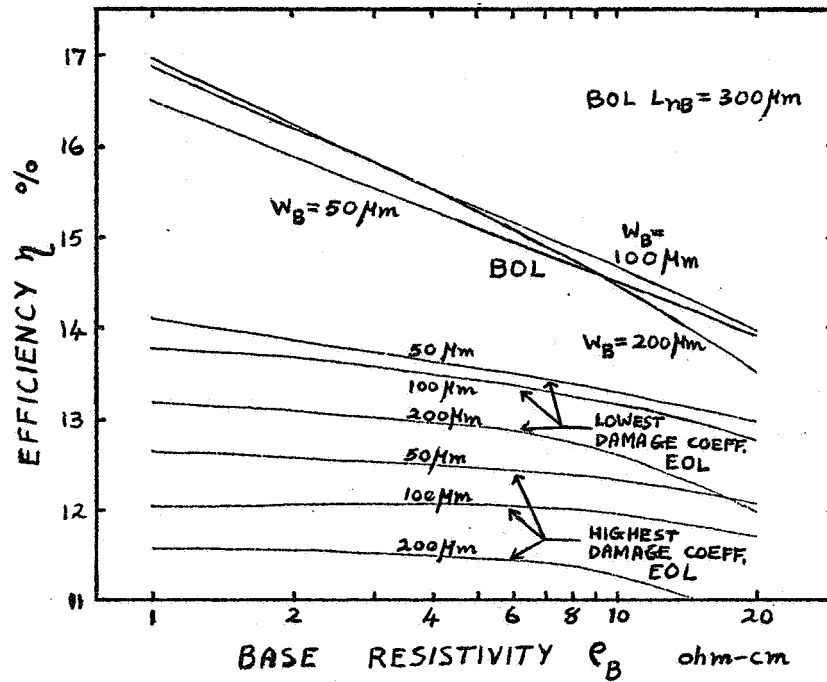


Figure 8. BOL and EOL Efficiencies versus Base Resistivity.